

The Behavior of Environmentally Friendly Corrosion Preventative Compounds in an Aggressive Coastal Marine Environment

Eliza L. Montgomery
ESC – Team QNA
Mailstop ESC 5
Kennedy Space Center, FL 32899

Jerome C. Curran
ESC – Team QNA
Mailstop ESC 5
Kennedy Space Center, FL 32899

Luz Marina Calle
NASA
Mail Code: NE-L4
Kennedy Space Center, FL 32899

Mark R. Kolody
ESC – Team QNA
Mailstop ESC 5
Kennedy Space Center, FL 32899

ABSTRACT

The shift to use environmentally friendly technologies throughout future space-related launch programs prompted a study aimed at replacing current petroleum and solvent-based Corrosion Preventive Compounds (CPCs) with environmentally friendly alternatives. The work in this paper focused on the identification and evaluation of environmentally friendly CPCs for use in protecting flight hardware and ground support equipment from atmospheric corrosion. The CPCs, while a temporary protective coating, must survive in the aggressive coastal marine environment that exists throughout the Kennedy Space Center, Florida. The different protection behaviors of fifteen different soft film CPCs, both common petroleum-based and newer environmentally friendly types, were evaluated on various steel and aluminum substrates. The CPC and substrate systems were subjected to atmospheric testing at the Kennedy Space Center's Beachside Atmospheric Corrosion Test Site, as well as cyclic accelerated corrosion testing. Each CPC also underwent physical characterization and launch-related compatibility testing. The initial results for the fifteen CPC systems are reported.

Key words: corrosion preventive compound, CPC, spaceport, environmentally friendly, atmospheric exposure, marine, carbon steel, aluminum alloy, galvanic corrosion, wire on bolt.

INTRODUCTION

The objective of the work presented in this paper is to determine if environmentally-friendly CPCs will provide adequate temporary corrosion protection for spaceport structures and related hardware used at the Kennedy Space Center (KSC). Typically when a bare metal surface could or should not be coated with a permanent coating (paint or sacrificial coating), a temporary coating, Corrosion Preventive Compound, CPC, is used to protect the exposed surface from corrosion. CPCs commonly contain corrosion inhibitors suspended in a mixture of solvents and a base oil or grease. The base oil acts as a carrier fluid for the inhibitors and also a protective barrier to environmental elements. The solvent acts as a base oil and inhibitor dispersant and is intended to evaporate after application. CPCs can be soft or hard films, and can be primarily composed of a petroleum, hydrocarbon, or fluoropolymer material depending on their end user requirements. Although CPCs provide corrosion protection, there are a number of environmental and safety issues:

- Base oils are not environmentally benign
- Solvents can be high in volatile organic compounds (VOCs) and toxic
- Corrosion inhibitors can be toxic
- Worker safety issues

Current petroleum-based CPCs are becoming increasingly impractical for use at this location due to environmental concerns and cumbersome containment procedures required during application and removal. These difficulties are encountered in the field, where nearly all CPCs are applied at KSC, and thereby CPC use at KSC has not been fully realized. KSC is known to be one of the most corrosive places in North America,¹ and CPCs offer a much needed option for corrosion protection to metallic materials that cannot be painted or will only be exposed to the corrosive atmosphere for a temporary time period. KSC is located within the Merritt Island National Wildlife Refuge; therefore, environmentally-friendly alternatives are highly sought after. Identifying successful environmentally-friendly CPC alternatives will relieve environmental and worker safety concerns, and also open new avenues for CPC use across KSC that were previously avoided. This paper focuses on the use of soft film CPCs, including common petroleum-based types and environmentally-friendly alternatives. Corrosion evaluations were performed at KSC's Beachside Atmospheric Corrosion Test Site.

BACKGROUND

CPC Applications of Interest at NASA

CPCs for Ground Support Equipment at Kennedy Space Center.

The Corrosion Control and Treatment Manual, TM-584C⁵, highlights multiple applications where CPCs are to be used to control corrosion of materials in facilities, systems, and equipment at KSC. The manual cites for CPC use in the protection of exposed bearing surfaces, tubular structural steel, electrical connectors, steel cabling, piano-type hinges, adjustable parts, and bare metal piston surfaces using corrosion inhibiting lubricants in the form of oil and greases. The manual cites several military specifications to refer to many of the NASA approved CPC types. The specifications are listed as: MIL-PRF-16173E⁶ (NAVSEA), grades, 2, 3, and 4, MIL-DTL-23549D⁷ (NAVAIR), MIL-PRF-81322G⁸ (NAVAIR), MIL-PRF-46000D⁹ (Army), MIL-PRF-46010D¹⁰ (Army), and MIL-PRF-46002D (Army).¹¹

CPCs are used for temporary corrosion protection on both bare metal and coated, often damaged, surfaces on ground support equipment, including but not limited to the Mobile Launcher Platform (MLP), the fixed service structures at the Launch Pads, the Crawler-Transporters. One major use is on the Thrust Vector Control (TVC) frames that structurally support components of the TVC system that is located in the aft skirt of the Solid Rocket Booster (SRB).³ TVC frames are exposed to the seacoast environment after refurbishment, seawater immersion after splashdown, and during tow-back to refurbishment facilities. During refurbishment operations it was found that numerous TVC frames were

experiencing internal corrosion and coating failures, both from salt air and seawater intrusions. Inspectors using borescopes would visually examine the internal cavities of the complicated aluminum alloy welded tubular structure. It was very difficult for inspectors to examine cavity corners and tubing intersections and particularly, to determine the extent of the corrosion and coating anomalies. Physical access to TVC frame internal cavities for corrosion removal and coating repair was virtually impossible, and an improved method using a CPC for preventing initiation of new corrosion, and mitigating and/or stopping existing corrosion growth has been used ever since.³

CPCs are used on the ISS for the iLIDS, which is a government furnished connector design made for anyone to manufacture and dock to the ISS. The iLIDS components consist of mixed metals, such as aluminum alloys (UNS A92219, UNS A92024, and UNS A97075), Stainless steels, titanium (for hook assembly), and UNS S44004 and UNS G52986 high alloy steel (for bushing and bearing materials), and Aluminum-bronze (for bushings and pins). There are issues with faying surfaces and galvanic couples that are corrected using CPCs.¹³ One problem noted was that, although the more corrosion resistant alloy UNS S44004 is specified, the less corrosion resistant alloy UNS G52986 is often used due to alloy availability issues. Should this problem continue, extra corrosion precautions will have to be taken that will require an increased use in temporary CPC coatings.¹³

In the past, CPCs were used on the Space Shuttle orbiters to cover paint nicks between repairs.¹⁴ Because the CPCs must survive the launch environment, Low Earth Orbit, and other flight cycle environments, thickened grease materials were used. The greases are often fluorinated vacuum greases with corrosion inhibitor additives.^{13,15} When the Space Shuttles were flying, the frequency of corrosion issues on the orbiters regularly exceeded 400 cases annually.¹⁶ Typically locations where CPC are used on the orbiters were the rudder speed brake, vertical tail, elevons, wing leading edge, ET door cavity, and body flap.¹² The longest time a CPC protected the substrate was four mission cycles.¹³

One problem that has been identified as a possible future use for CPCs at NASA is to temporarily cover space flight hardware that consist of bare metal components prior to launch. Current material specifications require that all manufacturers' coatings (usually CPCs) be removed prior to use. When space flight hardware is exposed to KSC environmental conditions, awaiting launch, atmospheric corrosion occurs on the surface. A temporary CPC coating that could be removed prior to launch would be considered an ideal solution to this problem.¹⁷

CPC Applications throughout DoD and Aerospace Industry

CPC are used heavily throughout the DoD in aircraft, ship, transport vehicle, and armored vehicle applications, as well as on many types of ground support structures and munitions. From a materials perspective, metal substrates are clearly used in the majority of vehicles and structures, therefore the opportunities for corrosion problems abound. It is estimated that the cost of corrosion to the DoD is estimated between \$10 billion and \$20 billion annually.¹⁸ Because DoD locations exist worldwide, there are many different environments that the DoD corrosion control personnel must deal with. The harshest are those that are close to or in seawater environments because sea salts accelerate the corrosion process.

Aircraft Applications.

Aircraft face some of the most common corrosion problems throughout the DoD and in the general aerospace industry. The constant cycling of wetting and drying due to condensation that occurs during take-off and landing is a root cause of much of the corrosion problems. Because of the shape of aircraft, there are many crevices and occluded areas built into the design that become traps for moisture. Aircraft have many components that are bare metal, as the substrates are almost always aluminum-based alloys. The lack of a protective layer, other than the natural oxide film, makes the substrate more likely for corrosion to form. Services, including the U.S. Air Force, Marines, Army, and

NAVAIR, all face the same types of problems with their aircraft regardless of type. The most common areas of corrosion where CPCs are used include beams, joints, fastener areas, electrical wiring components,¹⁹ inner and outer mold lines, cargo floor end fittings, fuselage belly skins, wheel well aft bulkheads, mainframes, stringers,²⁰ landing gear, flapwells,²¹ lap joints, beneath the floorboards in the bilge areas,²² the lavatory and galley, wing interior sections, doors and hatches, skin panel faying surface.²³ The F-18 has had some of the most severe corrosion problems thus far because dissimilar metals and a lack of drain holes for moisture build-up were flaws inherent to the design. CPCs have been used to control this type of corrosion, ever since the problems first surfaced.²⁰

Marine Applications.

Much of the vehicles used in marine applications, especially those deployed at sea, use paints and cathodic protection to manage corrosion because they need more permanent solutions to block the direct metal contact with the seawater. One common vehicle that routinely uses CPCs for corrosion control is the Expeditionary Fighting Vehicle (EFV). This vehicle is an amphibian type that sees both seawater, freshwater, and many cycles of drying. The seal frame, armor panel frame, threaded inserts, fasteners, and the environmental seal areas are the most common places that CPCs are used.²⁴

Ground Operations Applications.

Ground operations face multiple corrosion problems with fixed structures, transport vehicles, and armored vehicles. The Army and Marines have the common problems with corrosion on the ground. CPCs are heavily used for electrical hardware, fuel cell rooms,²⁵ occluded sites (hinges, fasteners, under lap seams),²⁶ and hydraulic lifts.²⁷ Both transport and armored vehicle types, including HMMWVs, trucks, MTRVs, and ITVs heavily use CPCs as a last layer of corrosion defense over their vehicle paint.²²

Launch Applications.

Non-NASA launch vehicles and structures also face critical corrosion issues. In 2008, Space Exploration Technologies faced a failure of their Falcon 1 launch due to a corroded aluminum bolt.²⁸ Depending on their location to seawater, launch structures will face differing degrees of corrosion; however, corrosion will most commonly exist on the fixed structures (fasteners, exposed metal, and all areas similar to those identified to in the NASA Corrosion Control and Treatment Manual), the rocket interior and exterior, the fuel cell areas, and the mixer assembly areas.²⁹

CPC Technologies

Current CPC Technologies.

Since the beginning of their use, CPCs have primarily been comprised of petroleum-based carrier oils, corrosion inhibitors, surfactants, and solvents.^{30, 31, 32} The use of petroleum gives CPCs an unlimited shelf life, because the oils slowly oxidize over time. In general, these petroleum-based products require personal protection equipment during use and are harmful to the natural environment if spilled.³³ Some CPCs are made using a lanolin-based carrier oil³⁴ or a high grade machine oil.³⁵ The CPC manufacturers' have begun to lower the solvent content in their CPCs so that they have low Volatile Organic Components (VOCs).³⁶ This effort is primarily due to public demand to make the CPCs less harmful to the environment.

Environmentally Friendly CPCs: State of the Art.

New CPC products are being made with canola, soy, and other vegetable-based carrier oils.^{37, 38} These products are also made so that they are solvent free, thus they contain no VOCs. The advantage to these products is that they are non-toxic and are easy to dispose of. They are made with no carcinogenic compounds or hazardous materials. There are questions as to the durability of these new plant-based CPCs, as the carrier oils are more likely to degrade at a faster rate than their petroleum-based counterparts. Because CPCs are meant, in most cases, to be used as a temporary line of

defense from corrosion, many CPC manufacturers claim that their products perform the same as or better than petroleum-based products as a temporary protection in the normal use time.

Challenges at NASA Kennedy Space Center

NASA KSC's Beachside Atmospheric Corrosion Test Site has been documented as the most corrosive place known in the United States.¹ Figure 1 displays the location of KSC and the beachside test site along Florida's Atlantic coast. The environmental challenges at KSC are both natural and man-made. The already higher-than-typical aggressive marine conditions are intermittently enhanced by the emission of 70 tons of hydrochloric acid into the atmosphere during launches that use rockets with solid fuel. Despite the corrosive environment, launch structures are largely made using structural steel, namely AISI 1010 (UNS G1010). Different coatings, such as sacrificial coatings and paints, are used to slow corrosion in many areas; however, in areas where metals cannot be painted the corrosivity of the environment is blatantly recognized over time. CPCs are and may be used in the future in areas across KSC where spaceport-specific environments, such as liquid oxygen or hypergolic fluids, may also be used. Special consideration was made to account for compatibility issues with future launch environments.

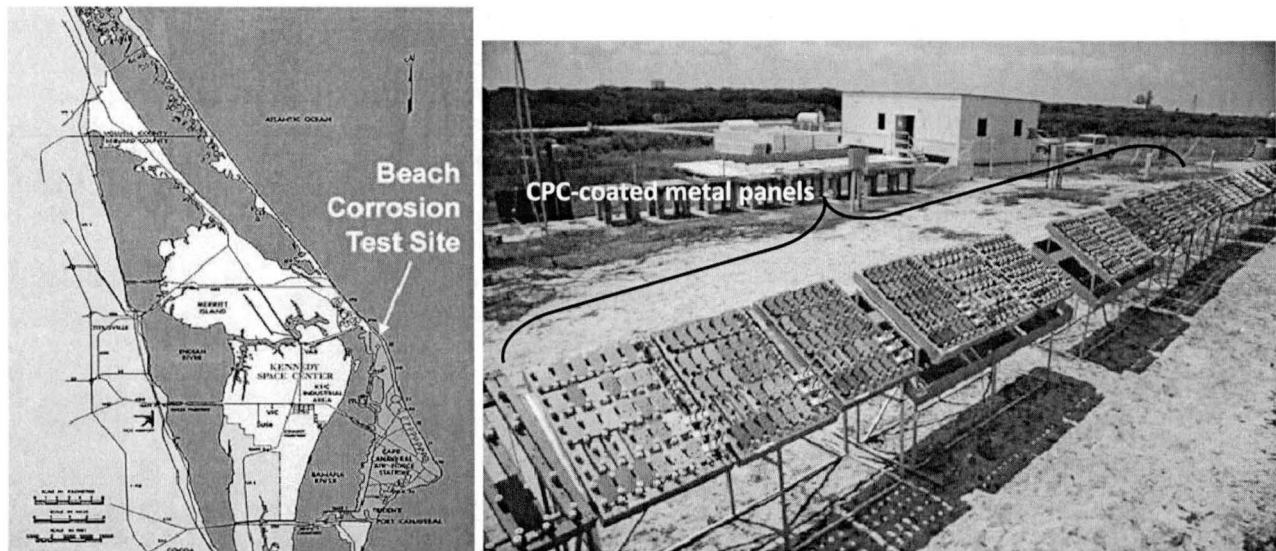


Figure 1: Location of NASA Kennedy Space Center's Beachside Corrosion Test Site along the Atlantic Ocean (left) and panels after initial CPC application and exposed to the marine atmosphere at KSC (right).

EXPERIMENTAL PROCEDURES

Test Plan Summary

Topics addressed in this study of environmentally-friendly CPC alternatives at KSC include:

- 1) Determining the physical properties of each CPC type in relation to their end use at KSC.
- 2) Determining the degree of corrosion protection that each CPC provides on various substrates.
- 3) Determining the compatibility of each CPC with NASA spaceport-specific environments.

This paper is based on work that is currently ongoing. The test plan, including alloys and CPC types, was chosen based on considerations for current and future possible end use of CPCs at KSC as well as other spaceport-related entities within the DoD and commercial space industry. Military specifications were considered and adopted where applicable. Table 1 displays the techniques and alloy types that are being used in the current test plan. Experimental details and results reported in this paper include: application characteristics, removability, long-term beachside atmospheric exposure,

crevice corrosion, galvanic corrosion via fasteners, wire on bolt atmospheric galvanic corrosion, stress corrosion cracking, and hypergol fluid compatibility.

Table 1
Experimental Test Plan Summary

Topic Number	Alloy Tested	Test Criteria
(Physical Characteristics)	UNS 10100	Application characteristics
	MIL-DTL-22759/87, MIL-DTL-22759/16	Wire compatibility
	UNS A92024	Removability
	UNS A93003	Wettability of CPC via contact angle
	UNS A93003	Hydrophobicity of CPC film on substrate via contact angle
	UNS A97075	Functional Penetration
	n/a	Viscosity
(Atmospheric Corrosion)	UNS 10100, UNS A97075, UNS A92219, UNS A92024	Cyclic Salt Fog
	UNS 10100, UNS S30403, UNS A97075, UNS A92219, UNS A92024	Long-term Beachside Atmospheric Exposure
	UNS S30403, UNS S31603, UNS A97075, UNS A92219, UNS A92024	Galvanic/Crevice Corrosion via Fasteners
	UNS 10100, UNS C11000, UNS A01100	Wire on Bolt Atmospheric Galvanic Corrosion
	UNS A97075, UNS A92219, UNS A92024	Stress Corrosion Cracking (SCC)
	UNS S30403, UNS A97075, UNS A92219, UNS A92024	Sandwich Corrosion Test
(Spaceport Compatibility)	n/a	Hypergolic fluid compatibility
	UNS A96051	Upward Flame Propagation

A literature and vendor survey was conducted to down-select possible CPCs for use on ground support equipment at KSC. Although multiple CPC products are used at KSC, only one control was chosen, and the remaining CPC types were included for comparison purposes. For this project, environmentally friendly refers to CPCs that have low VOCs (less than 100g/L), are non-HAPs, and are non-toxic and non-carcinogenic. The new CPC candidates chosen for this study, Table 2, are designated as such.

Table 2
Corrosion Preventative Compounds Reviewed in this Study

	CPC Type	Number Designation for Testing	Product Classification	Primary Composition
Soft Film: Oily	Oily film	1	Control	Petroleum distillates
	Oily film	2	Comparison	Petroleum distillates
	Oily film	4	Comparison	Petroleum distillates
	Oily film	5	Comparison	High grade machine oil

	Oily film	6	Candidate	Canola oil
	Oily film	7	Candidate	Soy/Canola oil
	Oily film	8	Candidate	Soy and canola oil
	Oily film	9	Candidate	Lanolin
	Oily film	15	Candidate	High grade oil, biodegradable
Soft Film: Wax or Grease	Wax	10	Control	Petroleum distillates
	Wax	11	Comparison	Petroleum distillates
	Wax	12	Comparison	Petroleum distillates
	Wax	13	Candidate	Soy and canola oil based
	Grease	14	Candidate	Soybean oil and clay thickener

Physical Testing

Functional Penetration.

This test was completed to provide visual evidence of a CPC's ability to penetrate a crevice or faying surface. Sandwich panels were assembled in such a way that created a crevice. The panels were elevated on one end creating a 10 degree slope. A 1 ml by volume amount of CPC was poured on the surface and allowed to seep in the crevice over a 24 hour period of time. An example of the test assembly with the initial application of several CPCs is shown in Figure 2. The sandwich panels were separated and the area of penetration was calculated using a grid system. The grid was created from a transparency, where measurements were made in $\frac{1}{4}$ " x $\frac{1}{4}$ " sections across the crevice area. The number of squares covered by the CPC was divided by the total number of squares to get a percent penetration value.

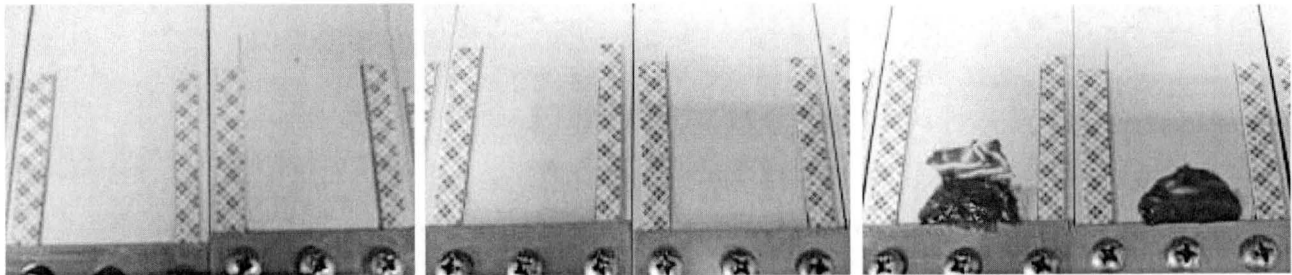


Figure 2. Functional Penetration assembly with examples of a soft film (7), wax (13), and grease (14).

Removability.

The CPCs were evaluated for removability using mineral spirits. A mineral spirit-soaked lint-free cloth was wiped across each CPC-coated panel surface for four continuous passes. The excess mineral spirits were wiped of the panel using clean lint-free clothes. Once dry, the panels were inspected for excess fill residue.

Atmospheric Corrosion Testing

Specimens were prepared for evaluation of long-term corrosion, crevice corrosion, stress-corrosion cracking, galvanic corrosion using fasteners, and galvanic corrosion using wires on bolt in atmospheric corrosion conditions. For atmospheric exposure testing, the specimens were placed at 30-degree angles towards the Atlantic Ocean at KSC's Beachside Atmospheric Corrosion Test Site. The test racks are located 150 feet from the high tide line, Figure 1. Each exposure rack consisted of specimens representing all of the different atmospheric corrosion tests. Each rack was treated with its

corresponding CPC type, where the CPCs were sprayed onto the specimens when possible or otherwise brushed on. The specimens were exposed for six months, from April through September 2012.

Panel Configurations.

The specimens for crevice corrosion, sandwich corrosion, and galvanic corrosion using fasteners were combined into a single configuration. Each panel consisted of two panels of the same alloy that were separated by CPC-soaked filter paper. The panels were attached using 316 SS (UNS S31603) washers. The washers were used to induce crevice corrosion and also for galvanic corrosion in combination with the aluminum alloys. The specimens for SCC were made using configuration a) in ASTM¹ G30. Specimens for long-term corrosion consisted of flat panels. The specimens for the wire on bolt galvanic corrosion were made according to ASTM G116. Photographs of the panel configurations are shown in Figure 3 and a photograph of the exposure racks after the initial atmospheric exposure is shown in Figure 1.

Corrosion Evaluation.

For the long-term corrosion testing, the weight loss method in ASTM G1²² was used to measure corrosion rates for the carbon steel panels, and the pitting corrosion method in ASTM G46 was used to measure corrosion of the aluminum alloys. The SCC and wire on bolt galvanic corrosion specimens were evaluated according to the ASTM specifications, G30 and G116 respectively. The crevice and galvanic corrosion using fasteners was evaluated by creating a grid of 1mm x 1mm squares in the same footprint as the washer. The number of squares relating to the galvanic corrosion were calculated and recorded as a percent of the total surface area. The crevice corrosion was calculated from the percent of the total circumferential area of the fastener where a crevice formed.

NASA Spaceport Environment Compatibility

Casual Contact with Oxidizers.

Casual contact with oxidizers was used to evaluate the effects on coatings from casual exposure to hypergolic fluids (nitrogen tetroxide (N_2O_4), hydrazine (N_2H_4), and monomethylhydrazine (MMH)). This procedure provides the method to determine if a fluid could react exothermally or spontaneously ignite on contact with a material. This test was necessary per NASA standards and was performed in accordance with NASA KSC MTB-175-88.³⁹ The CPCs were applied to aluminum foil weigh boats and evaluated in triplicate.

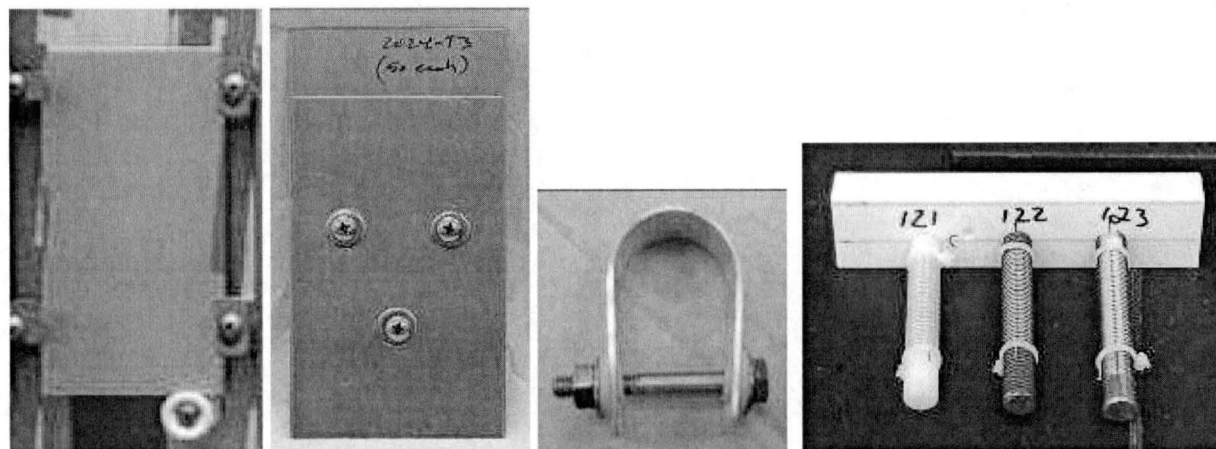


Figure 3: Specimen configurations for long-term atmospheric exposure (left), crevice and galvanic corrosion with fasteners and sandwich corrosion (middle left), stress corrosion cracking (middle right), and wire and bolt atmospheric galvanic corrosion (right).

¹ ASTM International, Conshohocken, PA, USA

RESULTS AND DISCUSSION

Physical Testing

Functional Penetration.

Table 4 shows the percent penetration of each CPC into the crevice after a 24-hour period. Interestingly, even the seemingly thicker and more static CPCs did penetrate into the crevice. For example, the thickest CPC, 14, eventually penetrated enough to result in 30 percent penetration across the crevice area. CPC type 10 penetrated at 28 percent. The remaining CPCs penetrated at or near 100 percent.

Removability.

All of the CPC types were easily removed; however, CPC types 10, 12, and 14 required twice as much effort, but were still considered easily removed. For all but three CPC types, a thin film residue remained on the surface after removal. CPC 12 had a slightly tacky film residue that remained after the initial film removal. Table 4 shows the CPC removability results.

NASA Spaceport Environment Compatibility

The oxidizer compatibility testing for the CPCs showed that two of the CPCs, 6 and 7, are incompatible with casual exposure to the oxidizer, where some smoking and color change occurred. Varying degrees of color change only was noted for six different CPCs, 1, 2, 4, 8, 12, and 13. This color change was not considered detrimental. The remaining six CPCs had no reaction to HNO_3 . The cumulative results are shown in Table 4.

Table 4
Functional Penetration, Removability, and Oxidizer, HNO_3 , Casual Exposure Capability Results

	CPC Type	Penetration	Removability	NASA Environmental Compatibility	
		Percent	Final Condition of Bare Substrate	Temperature Change	Observations
Soft Film: Oily	1	100	All removed	2.0	Color change; clear → yellow
	2	100	Thin film remained	2.2	Slight color change; clear → opaque
	4	100	Thin film remained	2.0	Color change; green → yellow
	5	100	All removed	1.5	None
	6	100	Very thin film remained	3.1	Smoking, bubbling. Color change; red → orange
	7	100	Very thin film remained	2.7	Small amount of smoking. Color change; yellow → brown
	8	100	Very thin film remained	3.6	Color change; pale yellow → dark yellow or orange
	9	100	All removed	2.6	None
	15	100	Thin film remained	2.6	None
Soft Film: Grease	10	28	Thin film remained	3.3	None
	11	100	Thin, tacky film remained	3.0	Slight color change; brown → darker brown

or Wax	12	79	Very thin film remained	2.9	Slight color change; yellow → darker yellow
	13	96	Thin film remained	4.1	None
	14	30	Thin film remained	1.8	None

Atmospheric Corrosion Testing

Long-term Atmospheric Exposure.

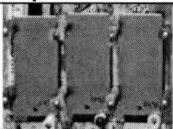
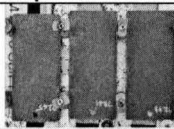
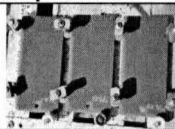
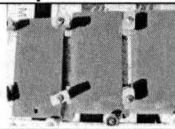
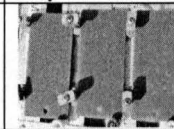
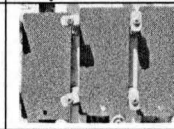
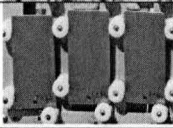
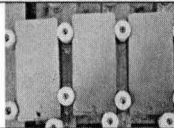
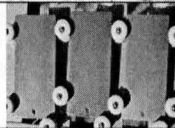
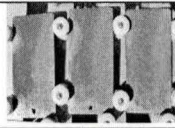
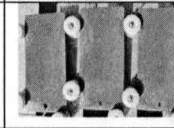
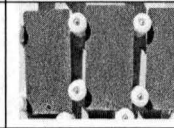
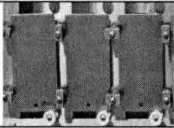
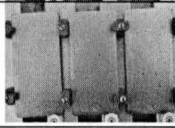
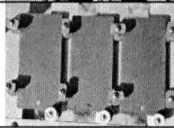
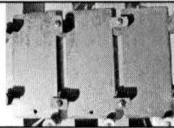
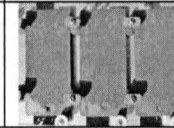
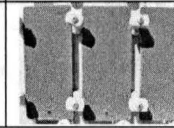
The atmospheric exposure results were most apparent for the CPCs on carbon steel, and Table 5 shows the progression of protection and corrosion after the initial twenty-two days of exposure. CPC types 9, 19, 11, 12, and 13 performed the best, but only CPC types 10 and 12 exhibited no corrosion products. All of the CPCs performed better than the control. After the twenty-two day period, CPC types 1, 2, 4, 5, and 15 CPC types seemed to have been severely degraded by the UV, moisture, and high temperature conditions at the exposure site. The mass loss results for the 6-month exposure period, Figure 4, show that all of the CPC types performed better than or nearly the same as the Control CPC, 1, and all performed better than the untreated carbon steel specimens.


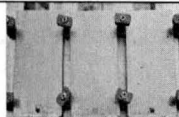
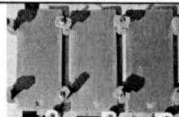
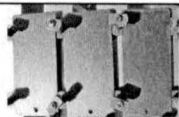

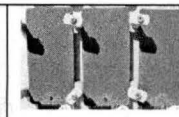
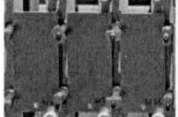
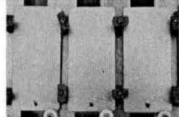
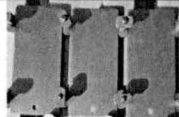

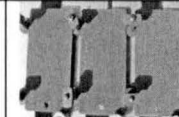
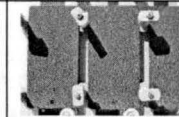
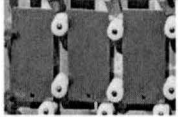
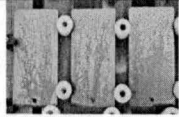
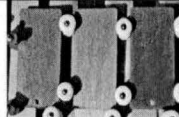
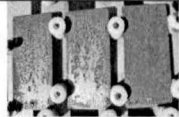
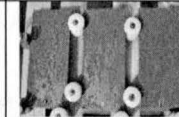
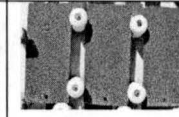
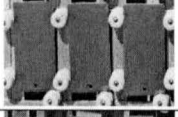
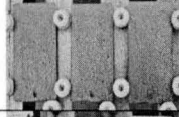
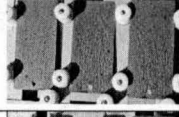
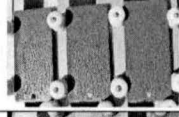
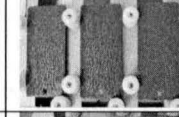
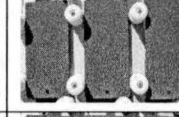
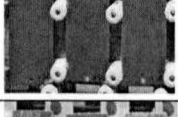
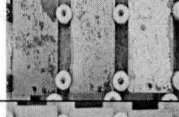
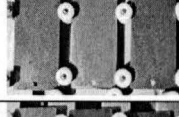
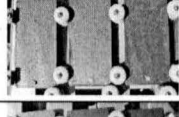
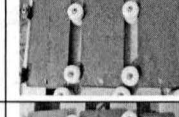
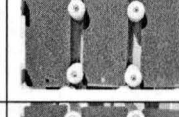
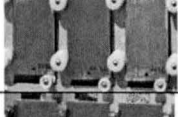
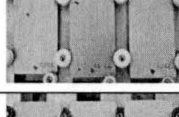
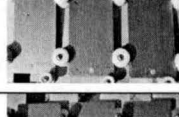
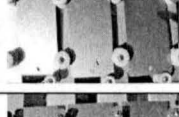
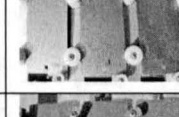
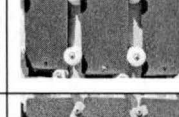
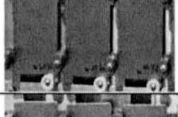
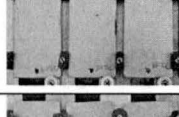
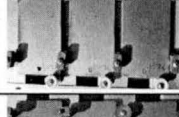


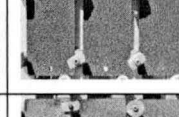
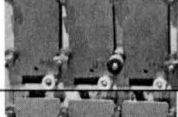
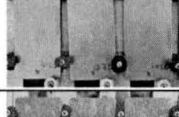
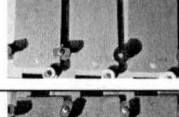

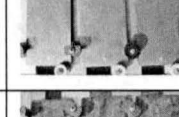
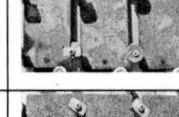
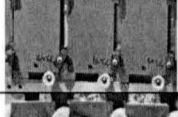

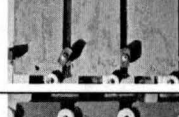



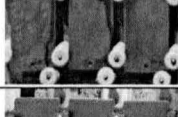
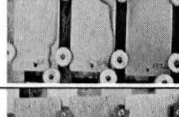
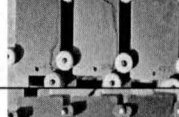
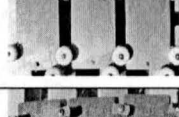
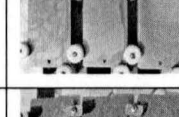

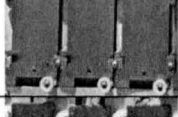

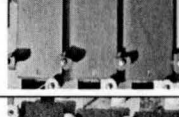




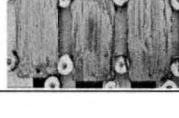

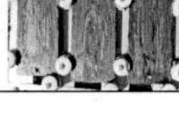
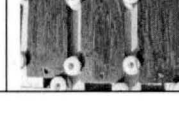
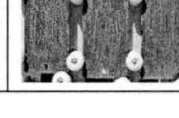
The aluminum and stainless steel alloys were rated for pitting corrosion and staining (steel only), which was present for all of the specimens, except those treated with CPC 10. Examples of typical pitting corrosion results is shown in Figure 5, where the blank 7075 alloy is shown along with CPC types 4 and 10. The pitting ratings were performed according to ASTM G46, where only the pit density (a) and pit size (b) were examined at this point. Methods are currently being considered to consistently measure the pit depth (c). Table 6 shows the pit density and size for all of the alloys.

Crevice and Galvanic Corrosion.

The crevice and galvanic corrosion analysis was performed of the sandwich panels in the area where the 316 SS washer and the substrate were in direct contact. The crevice and galvanic analysis were recorded as a percent of the total area affected by corrosion. Figure 6 shows examples of both stainless steel and one of the aluminum alloys where crevice corrosion was evident. In this figure, both the stainless steel blank and CPC-treated specimens had crevice corrosion, while the aluminum alloy (7075) exhibited both extensive galvanic and crevice corrosion from the dissimilar metal contact even in the presence of the CPC film. It is important to note that the washers were fastened prior to the CPC treatment.

Table 5
CPC-coated Carbon Steel Panel from Initial Exposure through 6 Months.

CPC Type	0 days exposure	3 days exposure	6 days exposure	13 days exposure	22 days exposure	6 months exposure
Blank						
1						
2						

4						
5						
6						
7						
8						
9						
15						
10						
11						
12						
13						
14						

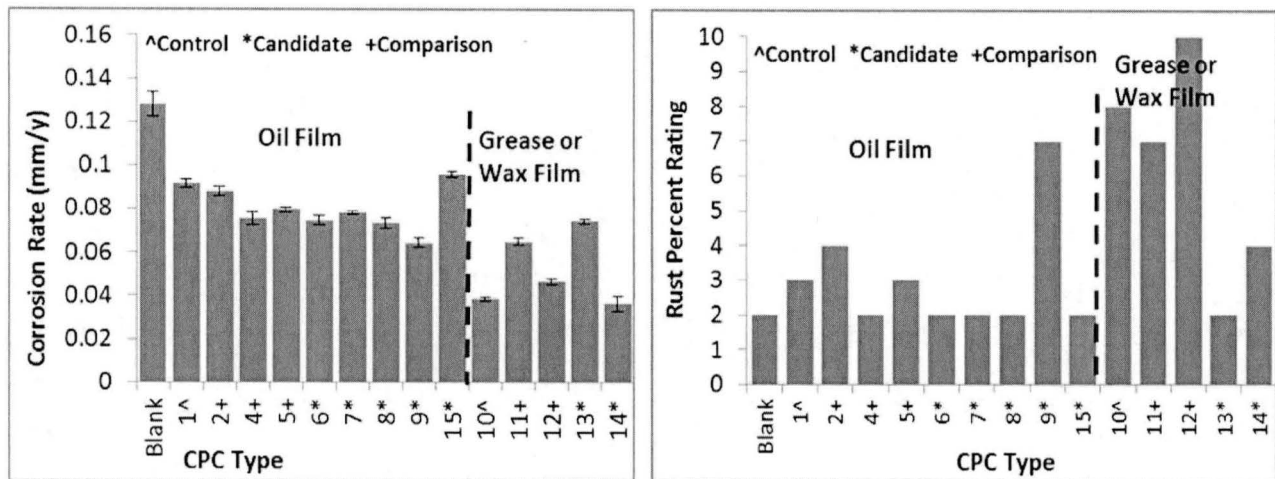


Figure 4: Mass loss results for long-term atmospheric exposure of CPC-coated carbon steel (left), and corrosion ratings of CPC-coated stainless steel panels (right) exposed to KSC's Beachside Atmospheric Corrosion Test Site for six months.

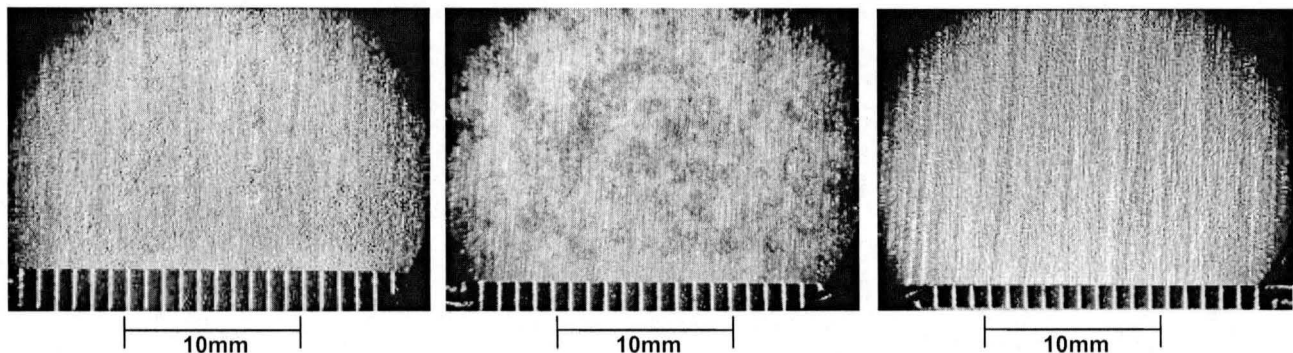


Figure 5: Examples of pitting results for long-term atmospheric exposure of CPC-coated aluminum alloy 2219: Blank (left), CPC 4 (center), and CPC 10 (right).

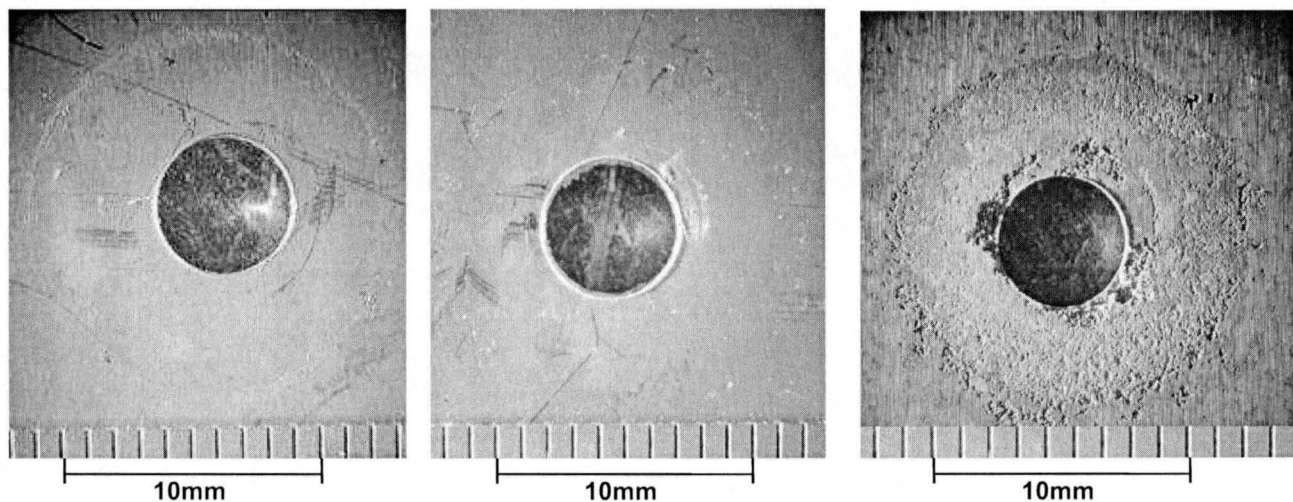


Figure 6: Examples of crevice corrosion for atmospheric exposure of CPC-coated stainless steel (left - blank and center- CPC 6), and crevice and galvanic corrosion of aluminum alloy 7075 (right -CPC 7).

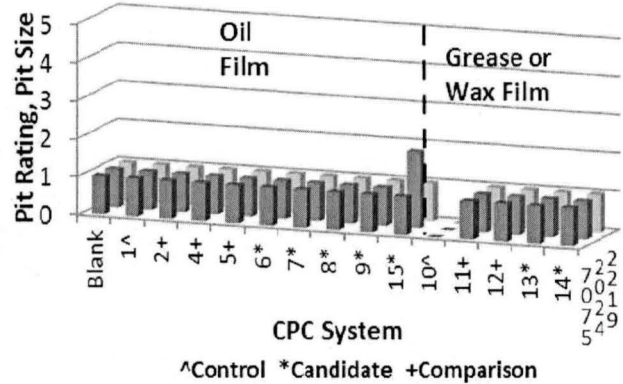
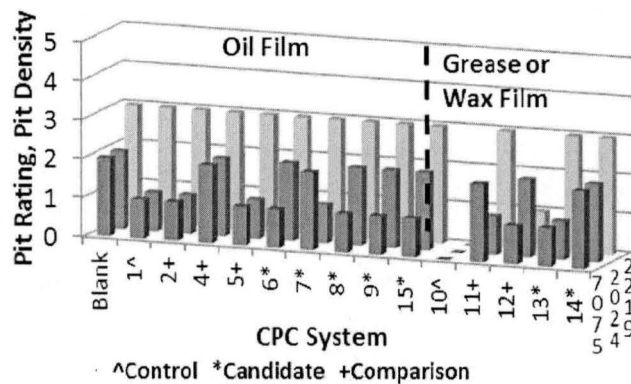


Figure *. Pit density and size results of CPC-coated aluminum alloy panels exposed to KSC's Beachside Atmospheric Corrosion Test Site for six months.

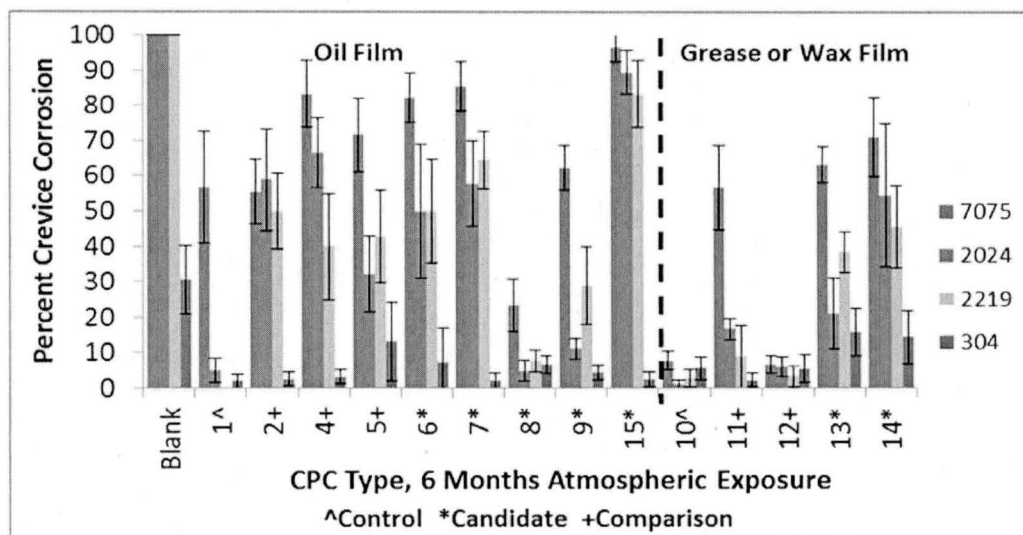


Figure *. Percent crevice corrosion via fasteners results of CPC-coated aluminum and stainless steel panels exposed to KSC's Beachside Atmospheric Corrosion Test Site for six months.

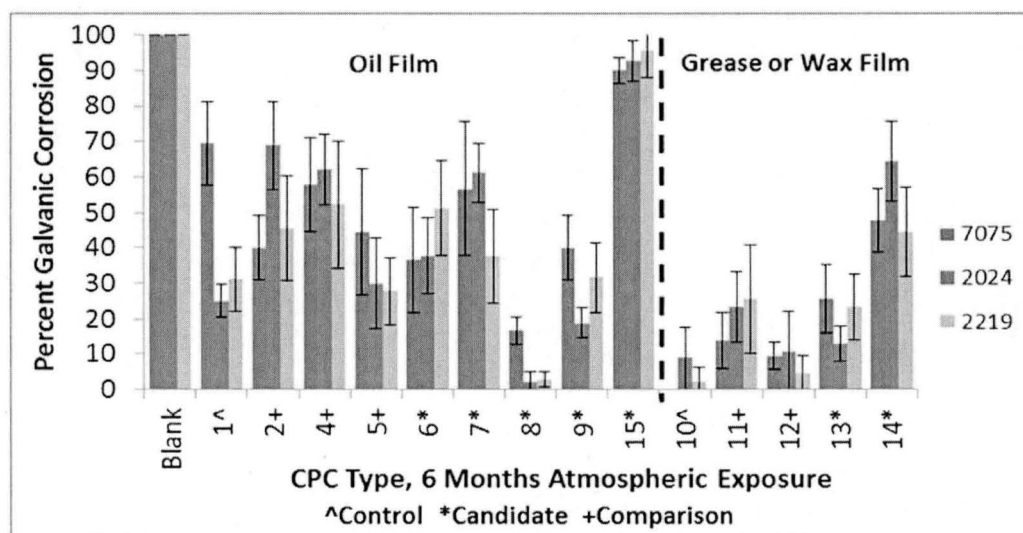


Figure *. Percent galvanic corrosion via fasteners results of CPC-coated aluminum alloy panels exposed to KSC's Beachside Atmospheric Corrosion Test Site for six months.

Stress Corrosion Cracking.

None of the stress corrosion cracking specimens, including the control, exhibited any degree of cracking after the 6 month exposure period.

Wire on Bolt Atmospheric Galvanic Corrosion.

Analysis of the data in Figure 7 clearly shows that CPC types 1, 8, 9, and 12 provided the most effective protection against corrosion for both the aluminum-iron and aluminum-copper galvanic couples. Although other CPC types were successful against the iron-based galvanic corrosion, a CPC will be considered successful if the more aggressive copper galvanic corrosion is also protected. None of the CPCs accelerated corrosion since they all exhibited mass losses lower than the control, designated as Blank.

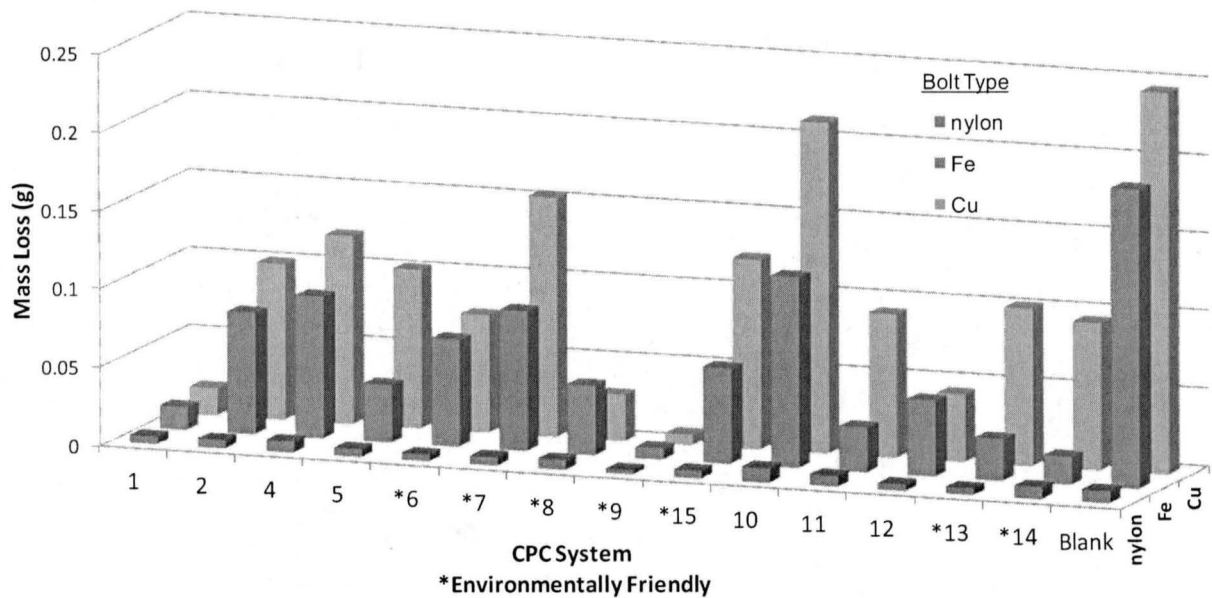


Figure 7: Mass loss results for wire on bolt galvanic corrosion.

SUMMARY

Although this work is still in progress, a summary of current results and analysis can be made.

- All of the CPCs, whether environmentally-friendly candidate or petroleum-based for comparison, performed better than the untreated specimens and better than or similar to the control CPC.
- All of the CPCs exhibited some crevice and galvanic corrosion in the galvanic corrosion with fasteners evaluations. CPCs 8, 10, and 12 exhibited the least amount of both crevice and galvanic corrosion, seeming to have penetrated successfully under the fastener and provide relatively good protection considering the long atmospheric exposure time period.
- CPC 10 was the only CPC type to resist corrosion for all of the aluminum alloys, but it did not fare well in the wire on bolt galvanic corrosion testing. CPC 10 is not an environmentally-friendly CPC type.
- Ultimately the corrosion performance criteria will rely largely on atmospheric corrosion results for the time to initial failure. CPCs 1, 2, 4, 5, and 15 "failed" (for carbon steel, corrosion product covered the entire sample and the CPC film was removed) after 22 days of exposure, and CPCs 6, and 7 "nearly failed" as well.

- Only the exposure time factor can be controlled in the corrosion studies, as applying the same film thickness for all CPC types is neither practical nor comparable for this study. The performance differences are noted in relation to the film thickness, CPC type, and application technique. These variables will be considered when final selections are made, and contradiction to CPC performance between the different test criteria is considered.
- The remaining corrosion, physical, and spaceport compatibility testing is ongoing, and a second phase of the best-performing CPCs will continue in the next year. The CPC types cannot be ranked yet, and different CPCs will be categorized based on possible end-use applications, application frequency, and compatibility with other spaceport non-metal materials.

ACKNOWLEDGEMENTS

Special thanks to Teddy A. Back (ESC) and Robert Devor (ESC) for technical support.

REFERENCES

1. S. Coburn, "Atmospheric Corrosion Properties and Selection, Carbon Steels", Metals Handbook, Metals Park, American Society for Metals (1978) p. 720.
2. Simmons, J.R., "NASA CR-161431: Study of Etchants for Corrosion-Resistant Metals, Space Shuttle External Tank", Martin-Marietta Aerospace prepared for NASA – George C. Marshall Space Flight Center (1980).
3. Novak, H.L., Hall, P.B., "Environmentally Compatible Vapor-Phase Corrosion Inhibitor for Space Shuttle Hardware", 5th Conference on Aerospace Materials, Processes, and Environmental Technology (2003).
4. The Boeing Company, "Specification MF0004-135: Use of Corrosion Preventive Compounds on Space Shuttle Orbiter" (2006).
5. NASA, "NASA-TM-584C, Corrosion Control and Treatment Manual, November 1, 1994".
6. DoD, "MIL-PRF-16173E(SH), Performance Specification Corrosion Preventive Compound, Solvent Cutback, Cold-application, September 7, 2006."
7. DoD, "MIL-DTL-23549D, Detail Specification, Grease, General Purpose, May 10, 2002."
8. DoD, "MIL-PRF-81322G, Grease, Aircraft, General Purpose, Wide Temperature Range, January 24, 2005."
9. DoD, "MIL-L-46000 Lubricant, Semi-Fluid (Automatic Weapons), February 25, 1987."
10. DoD, "MIL-L-46010 Lubricant, Solid Film, Heat Cured, Corrosion Inhibiting, August 6, 2008."
11. DoD, "MIL-P-46002 Preservative Oil, Contact and Volatile Corrosion-Inhibited, January 20, 2010."
12. Shindo, D., NASA Johnson Space Center, Personal interview, September 20, 2011.
13. Dube, M. NASA Goddard Space Flight Center, Personal interview, October 11, 2011.
14. Patterson, J.D., "Boeing Lab Report No. M&P-3-1868: Corrosion Inhibiting Grease Study, August 24, 2007."
15. Hale, S., "Report No. SETS FPR23100.8: Identification of the Effectiveness of Current Coatings and Corrosion Preventive Compounds Used on the Space Shuttle Orbiter, September 9, 2005."
16. Hale, S., "Corrosion Preventive Compounds Lifetime Testing, United Space Alliance, April 19, 2007."
17. Dellacorte, C. NASA Glenn Research Center, Personal Interview, October 18, 2011.
18. CorrDefense, "Why DoD Must Protect its Assets", DoD Office of Corrosion Policy and Oversight website:
<https://www.corrdefense.org/CorrDefense%20WebPage%20Content/WhyDoDMustProtectItsAssets.aspx>.
19. Jones, S. "C-130 CPC Application and Evaluation Program", 2003 Air Force Corrosion Conference (2003)

20. McTish, D., Jones, S., "C-5 Corrosion Prevention Compound Application Program", 2005 Air Force Corrosion Conference, March 14-17, 2005.
21. Abbott, W. "A Decade of Corrosion Monitoring in the World's Military Operating Environments, A Summary of Results", 2008. ", DoD Office of Corrosion Policy and Oversight website: <https://www.corrdefense.org/Academia%20Government%20and%20Industry/A%20Decade%20of%20Corrosion%20Monitoring.pdf>
22. Shah, S.R., Shoales, G.A., Fawaz, S.A., "Lap Joint Integrity and Corrosion Preventive Compound Evaluation Using Electrochemical Impedance Spectroscopy." DoD Office of Corrosion Policy and Oversight website: [http://saf-engineering.com/Publications/ASIP2008%20Lap%20Joint%20Integrity%20and%20Corrosion%20Preventive%20Compound%20\(CPC\)%20Evaluation%20using%20Electrochemical%20Impedance%20Spectroscopy%20\(EIS\).pdf](http://saf-engineering.com/Publications/ASIP2008%20Lap%20Joint%20Integrity%20and%20Corrosion%20Preventive%20Compound%20(CPC)%20Evaluation%20using%20Electrochemical%20Impedance%20Spectroscopy%20(EIS).pdf)
23. Arafat, E., "High Performance Corrosion Preventive Compound for Internal Aircraft and Other Weapon System Applications", ESTCP Project WP 0615, Final Report, November 15, 2010.
24. Arafat, E., "Demonstration/Validation of High Performance Corrosion Preventive Compound for Interior Aircraft Applications", SERDP/ESTCP Workshop, Tempe AZ, February 26-28, 2008.
25. "Army Aviation", 2005 Air Force corrosion Conference, March 14-17, 2005.
26. Price, K., Dante, J. "CPC Performance in Occluded Sites", 2005 Tri-Service Corrosion Conference.(2005)
27. Ferris, D., Darter, K., Hays, R. "US Marine Corps Corrosion Programs", 2004 Air Force Corrosion Conference, March 9, 2004.
28. Berger, B., "Falcon 1 Failure Traced to a Busted Nut", Space.com, July 19 2006. <http://www.space.com/2643-falcon-1-failure-traced-busted-nut.html>.
29. Ellicks, D., Bloyer, J., "Alternative Coatings for Missile Launch Support", 2004 Air Force Corrosion Conference (2004).
30. Gui, F., "Novel Corrosion Schemes for the Aerospace Industry, Corrosion Control in the Aerospace Industry," Benavides, S. editor, Woodhead Publishing Limited, Cambridge, England (2009) p249.
31. Corrosion Technologies Corporation, "Corrosion X MSDS" (2011).
32. Cortec Corporation, "VpCI-368 MSDS" (2011).
33. PMS Products, Inc., "Boeshield T-9 MSDS" (2011).
34. Eureka Chemical Company, <http://www.fluid-film.com/environment/index.html>.
35. Akin, K.D., "Greases and Their Role in Corrosion Control in the Aerospace Industry", Benavides, S. editor, Woodhead Publishing Limited, Cambridge, England (2009) p267.
36. NAVAIR, Office of Research and Technology Applications, NAVGUARD, "Navy Case #95904 and Nacy Case #97473" (2006).
37. Cortec Corporation, "EcoLine 3220 MSDS" (2011).
38. Renewable Lubricants, Inc., "Bio-Medium Preservative Liquid MSDS" (2008).
39. NASA KSC MTB-175-88: Procedure for Casual Exposure of Materials to Hypergolic Fluids, Test Method 7.1, Reactivity Test Method.